FACTORS AFFECTING 'END OF DAY' WINDOW POSITION IN NON-AIR-CONDITIONED OFFICE BUILDINGS

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ABSTRACT

This paper reports a recent longitudinal study observing people's use of windows in cellular office spaces and suggests that the thermal environmental parameters are not the only factors affecting people's behaviour. The study focuses on the 'end-of-day' window position due to its influence on the next day's thermal performance of buildings and energy use during the unoccupied night-time period when occupants' comfort is not important. The results suggest that the occupant behaviour determining the final window position at the end of the working day dependents not only on temperature, but also on floor level, gender and personal preference.

INTRODUCTION

In non-air-conditioned buildings, occupants are able to adjust their indoor environment by using available adaptive opportunities such as opening a window or taking off extra clothing layers (Baker and Standeven, 1997). Most studies in this field focused on occupants' operation of windows, since the window links the internal and external environments and has a significant impact on the environmental conditions of a building. A detailed literature review regarding occupants' adaptive behaviour in buildings can be found in Wei et al. (Wei et al., 2010).

Several early studies of human adaptive behaviour showed that the operation of windows was dependent on the temperatures indoors or outdoors. From a field study conducted in five office buildings from March to May, Warren and Parkins (WARREN and PARKINS, 1984) found that the proportion of open windows in office buildings had a strong correlation with the external air temperature, followed by the solar gain and wind speed. In addition, they suggested potential reasons for the opening and closing of windows in both winter and summer based on questionnaires filled out by participants in the study.

Fritsch et al. (Fritsch et al., 1990) proposed a model based on a Markov chain expressing that *'finding a window in a certain position depends only on its preceding position and not on any others'*. The outdoor air temperature was found to be a better driving parameter for predicting window position in winter compared to the indoor air temperature, wind speed and south vertical solar radiation.

Rigal et al. (Rijal et al., 2007, Rijal et al., 2009) carried out a series of field studies on people's thermal comfort and adaptive behaviour in a large number of non-air-conditioned buildings in European countries. The study showed that the proportion of open windows could be predicted using a combination of indoor and outdoor temperatures, and seasonal effects were also observed.

Over the past ten years, researchers found that human adaptive behaviour is influenced by the times of day. Yun and Steemers (Yun and Steemers, 2008) and Yun et al. (Yun et al., 2009) carried out a field study of window operation in two academic buildings in Cambridge in the summer of 2006. They suggested that indoor stimulus such as indoor air temperature is more appropriate than outdoor stimulus when predicting human behaviour indoors, because *'the indoor temperature varies with a range of factors, such as orientation, the design of an envelope, the thermal mass of the building structure, internal heat gains, etc.'*. In the 'Yun algorithm', therefore, the indoor air temperature was used as the driver for predicting window opening. They classified the time of day into 'arrival' and 'subsequent' periods because they found that occupants' operation of windows was significantly different between these two periods. To evaluate occupants' use of night ventilation in naturally ventilated buildings, Yun and Steemers (Yun and Steemers, 2010) carried out another field study in 3 offices located in two different buildings that allow secure ventilation. They suggested that indoor air temperature was a robust and reliable predictor of 'end of day' window position. Furthermore, wide variations in window-control patterns were observed among the monitored offices for all arrival, subsequent and departure periods.

Herkel et al. (Herkel et al., 2008) developed a model that considered window size, window opening size, time of year, outdoor air temperature and building occupancy patterns, based on a year-long field study monitoring the window operation in 21 south-oriented offices in Germany. The time of year was divided into winter and summer, based on two time points during the year: Summer to winter occurs as the date when the daily mean outdoor air temperature drops below 10°C for the first time; the change from winter to summer is defined as the first day when the daily mean outdoor air temperature exceeds 15°C. Herkel also made a classification of times of day as first arrival, intermediate arrival, intermediate, intermediate departure and last departure. The 'end of day' window position was defined according to the outdoor air temperature during the last departure period.

From 2001, Haldi and Robinson (Haldi and Robinson, 2009a) at EPFL, Switzerland carried out a significant longitudinal study monitoring occupants' window operation in their experimental building. Using multiple logistic regressions, they compared potential influencing factors including indoor and outdoor air temperatures, outdoor relative humidity, rainfall, wind speed and direction, absence from office, floor level and different times of day (classified as 'arrival', 'intermediate' and 'departure'). In their model, the 'end of day' window position was determined by two environmental parameters – daily mean outdoor air temperature, indoor air temperature, and one non-environmental parameter – floor level. They also observed significant variability between individuals' behaviour during the intermediate period (Haldi and Robinson, 2009b).

From field studies, many researchers found that human behaviour was also dependent on individuals' preferences. When modelling the manual control of lighting in buildings, Bourgeois et al. (Bourgeois et al., 2006) had classified daylight users as 'active' or 'passive'. Yun et al. (Yun et al., 2009) used similar terms to classify window users because they found variation in window use between occupants – during arrival, users were described as 'active', 'medium' and 'passive' window users based on a qualitative assessment of the logistic regression correlation characteristics of different occupants.

This classification approach is also found in the survey work by Rijal et al. (Rijal et al., 2007), where window users were classified as either active or passive based on results from self-reported questionnaires focusing on occupants' daily work, regardless of the time of day. The proportion of open windows for active users was demonstrated to be significantly higher than the one for passive users based on observed data. However, this finding had not yet been applied into their 'adaptive window-opening algorithm', and currently, there is still no standard method to categorise window users in this respect.

Summary and aims of the study

Keeping windows open overnight for a building can have a significant impact on the comfort performance in offices during the summertime in moderate climates such as for the UK (Kolokotroni et al., 1998). It can also have a significant impact on the energy consumption of buildings when heating is required, and so developing a better understanding of the determinants of 'end of day' window position is important. There have been numerous studies based on understanding window opening behaviour in buildings mainly based on thermal factors such as indoor or outdoor air temperature, and these have generated useful models for use in the building simulation. However, it is also clear that there are other factors that could affect this behaviour and the understanding of these issues is less well developed. Individual occupant behaviour or the behaviour of a particular group of individuals within a building population may vary and this could influence decisions about building layout, systems design, control and occupant education.

This paper contributes to the understanding of how important is the consideration of these 'other factors' for occupants' operation of windows in the office building.

EXPERIMENTAL

In this study, environmental and non-environmental factors are considered to determine possible influence on the 'end of day' window positions in offices. Five relationships were investigated using the data:

- Outdoor air temperature;
- occupant presence the following day;
- floor level;
- gender; and
- personal preference on window position during the night.

The subject building comprised of single-cell offices (depicted in Figure 1) regularly occupied by the same person, in order to minimise other influences that could affect behaviour, such as communication and negotiation with others within the working place. In this study, all participants have sole control over their environmental conditions.

The study was carried out from 20th June 2010 until 30th September 2010, in the Civil and Building Engineering Department building at Loughborough University, UK (52°45'54''N, 1°14'15''W, alt.70m). A total of 36 offices were observed and these were located on two orientations of the building facade; southwest and northwest. The building facade is curved and so the orientations of office windows on a given facade vary slightly. Outside the building, there is a layer of mesh facade, which is used to enhance the shading in summer. To some extent, this architectural feature helps to improve the security of the building, because it provides a physical barrier that prevents entry through an open window. Indoor air temperature was measured every 10 minutes by a Hobo UA-001 temperature sensor with an accuracy of ±0.47°C. It was located under the occupant's desk at the abdomen level, avoiding direct sunlight. The outdoor air temperature was measured by a local weather station on the roof of a nearby building (approximately 150m from the study building).

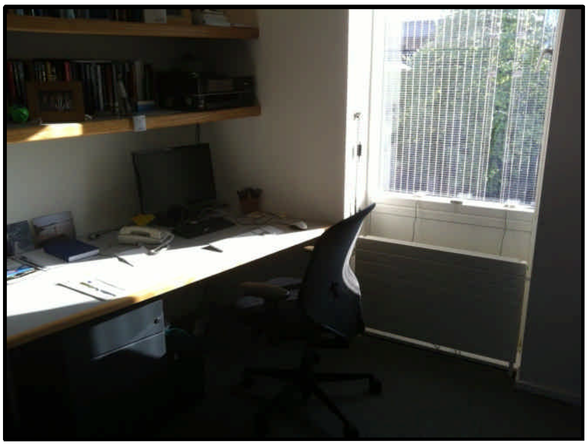

Figure 1 Typical cellular office in the building

The presence of occupants was checked by observation three times during the day between; 10:00am-10:30am (after most occupants have arrived), 11:30am-12:00pm (before lunch time) and 3:00pm-3:30pm (in the middle of afternoon) separately. The 'end of day' window position of each office was checked and recorded at about 8:00pm when occupants had (usually) vacated the building.

RESULTS

The results are presented here considering each of the five factors in turn, and considering the effect on the proportion of windows left open at the end of each working day.

Outdoor air temperature

Outdoor air temperature is a key factor that affects occupants' use of windows, and so correlations were made between outdoor air temperature and window position. 36 people took part in the study and their offices were observed over 72 working days, and there were 1360 'sample days' in total with occupied offices during the daytime. Each sample day was classified using discrete bins at 2K intervals. Each bin in these results contains at least 30 sample days, and at least 80% participants of the study are represented in each bin.

The outdoor temperatures were recorded at 3:00pm and 6:00pm since these are critical times in the working day of this particular building: at 3:00pm, occupants will usually be present if they are in the offices on that day and they have usually left before 6:00pm. Averaging these two temperatures gave a good estimate of the external temperature at the time when occupants would have left the offices for the day. A check was made on the variation of temperatures between these times and they were typically less than 2K. The results, shown in Figure 2, were not sensitive to this variation. Figure 2 demonstrates that the proportion of windows left open on departure is generally proportional to the outdoor air temperature. Considering the effect from the number of samples in each temperature bin, the 95% level confidence intervals calculated by the Adjusted Wald Method (Brown et al., 2001) are added. For the observed probability, it is not clear why there is a slight rise in the characteristic in the 15-17°C bin, this may be to do with the fact that at those temperatures a greater number of the samples were from one particular month (July) or other factors, such as sample size difference between those bins, could have played a role, but it is difficult to be certain. The rise, however, is small and the data shows a similar characteristic of operation of windows when compared with two published studies (Figure 3).

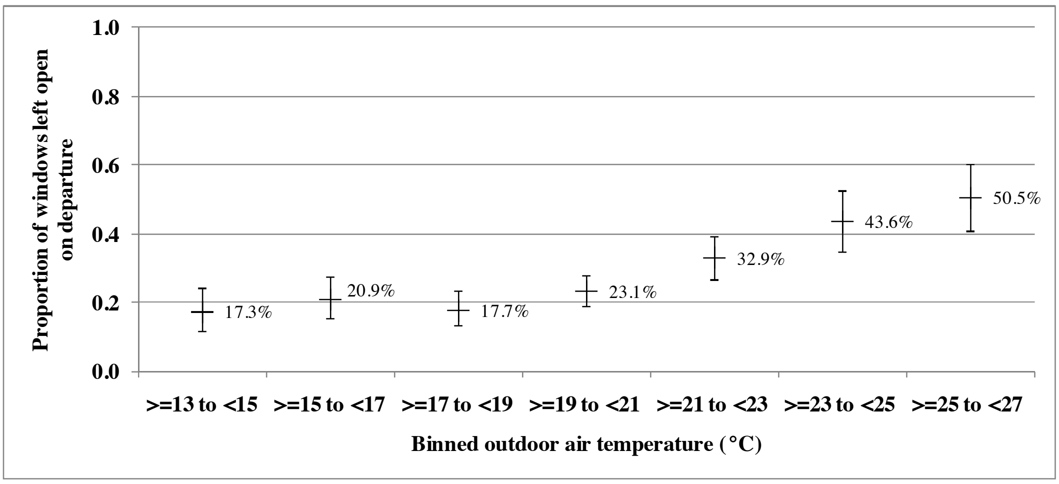

Figure 2 Proportion of open windows as a function of outdoor air temperature

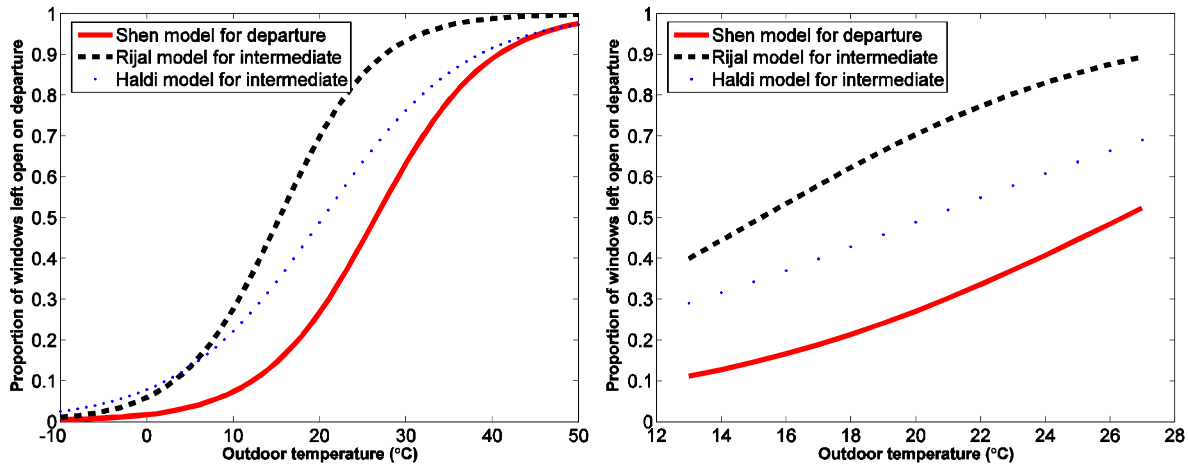

Figure 3 Comparison between the model created from the data in Figure 2 and two published studies: S-shape logistic regression models (left); Comparison in the same range of outdoor temperature as in Figure 2 (right)

The solid line in Figure 3 (left) shows an S-shape logistic regression model (Shen model for departure) generated from the data shown in Figure 2. The dashed line and the dotted line are from Rijal et al. (Rijal et al., 2007) and Haldi and Robinson (Haldi and Robinson, 2009a), respectively. Both of these published studies consider the window operation during the normal working time, rather than the end of the day. Figure 3 (right) shows these three models in the same range of outdoor air temperature as in Figure 2 (13°C to 27°C), where the minimum difference of the proportion of open windows between the Shen model and the Rijal model is 28.8%, while that between the Shen model and the Haldi model is 16.7%. As expected, the model created from this study suggests a higher probability of people closing windows when they leave the office.

Occupant presence the following day

An analysis was conducted to see if, when people were not in their offices at all in the *following* day, whether that had an influence on the 'end of day' window position. To evaluate the influence from this factor, only the samples from offices with male occupants on the 1st and 2nd floors are used, so there is no influence from the floor level and gender – the latter two factors will be discussed in later sections. The result is shown in Figure 4, which compares the proportion of windows left open on departure for different conditions of occupancy the following day (presence or absence). From the comparison, it could be found that the proportion of windows left open on departure is not significantly reduced if people are not in their offices the following day. The logistic regression analysis using outdoor air temperature and presence the following day as predictors of window position also supports this conclusion as the p value of the predictor presence the following day is 0.622, which is bigger than the critical value 0.05.

Floor level

Data from offices occupied by male subjects were used here to eliminate any potential effects from gender. Haldi and Robinson (Haldi and Robinson, 2009a) proposed that the 'end of day' window positions on the ground floor is significantly different from other floors in a building. The data from this study supported this finding as shown in Figure 5. From Figure 5, it can be seen that males working on the ground floor have a significantly lower probability (p values in logistic regression are both zero compared with first and second floors) to keep their windows open overnight than those working on the first and second floors, especially when the outdoor air temperature on departure is lower than 21°C. Furthermore, considering the 95% confidence intervals for each outdoor temperature bin, the biggest possible percentages for the ground floor are generally smaller or slightly bigger than the smallest possible percentages for the first and second floors. From this data sample, it is hard to confirm any significant difference between proportions of windows open on the first and second floors (the p value of the predictor floor level in the logistic regression is 0.425 between the first and second floors). There is an atrium in the building connecting the three floors and although stratification does occur, the observed characteristics reported here appear not to be contradicted when the indoor air temperature is used in the correlations.

One further comment is that the 'architectural mesh' surrounding the building may offer some apparent reduction in security risk. However, this requests further investigations.

Gender

If the first and second floors only are considered, then any security related influences are minimised, and it might be expected that the influences on behaviour are similar between these floors.

8 women and 18 men participated in the survey from the first and second floors of the building. Although the number of women is small, the possibility of gender as a significant factor was explored. Figure 6 shows the comparison between the proportions of windows left open as a function of outdoor air temperature for men and for women. In this data sample, it could be observed that the proportion of windows left open on departure for females is significantly lower than for males (the *p* value of the predictor gender in the logistic regression analysis is 0.000). Furthermore, considering the 95% level confidence intervals for each outdoor temperature bin, the biggest possible percentages for females is still smaller than the smallest possible percentages for males. Therefore, a significant impact from gender on behaviour could be identified.

Previous behavioural studies support the finding that behaviour can be gender dependent. Andersen et al. (Andersen et al., 2009) carried out a subjective survey by questionnaires in Danish dwellings and found out that gender has an effect on both use of windows and lights in Danish homes. Karjalainen (Karjalainen, 2007) conducted a quantitative interview survey to analyse occupants' thermal comfort and use of thermostats in homes, offices and a university. Significant gender differences in thermal comfort (females were less satisfied with room temperatures than males), temperature preference (females preferred higher room temperatures than males) and use of thermostats (females used thermostats less in households than males) were identified in his study. Parsons (Parsons, 2002) examined how people maintain their thermal comfort by adjusting clothing insulation levels and found that women tended to make more changes of clothing insulation than the men in the experiment. In a field study conducted in 22 air-conditioned buildings located in a hot-arid climate, Cena and de Dear (Cena and de Dear, 2001) proposed a difference between clothing insulation levels for females and males – the clothing insulation of females was about 0.1 clo lower than males in summer.

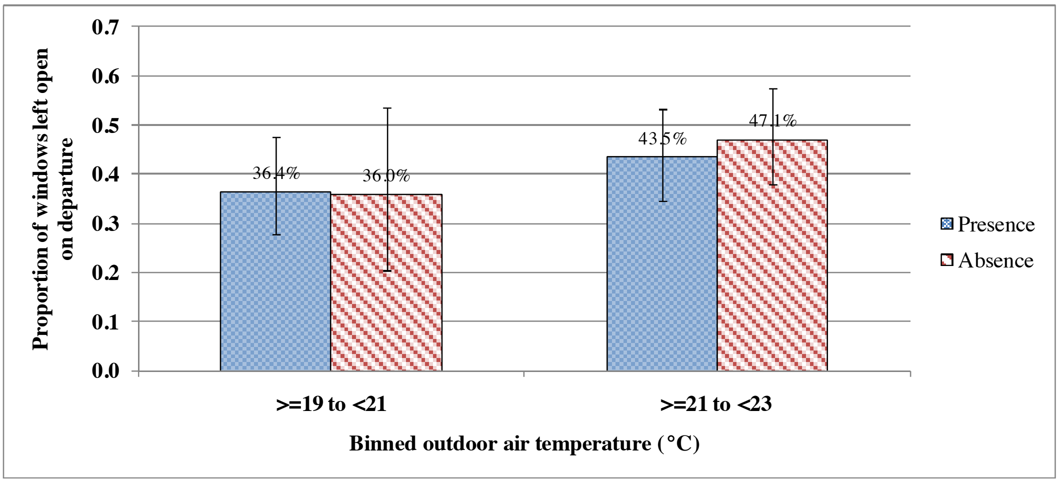

Figure 4 Proportion of windows left open as a function of outdoor air temperature for different conditions of occupancy the following day (18 offices with male occupants on the 1st and 2nd floors)

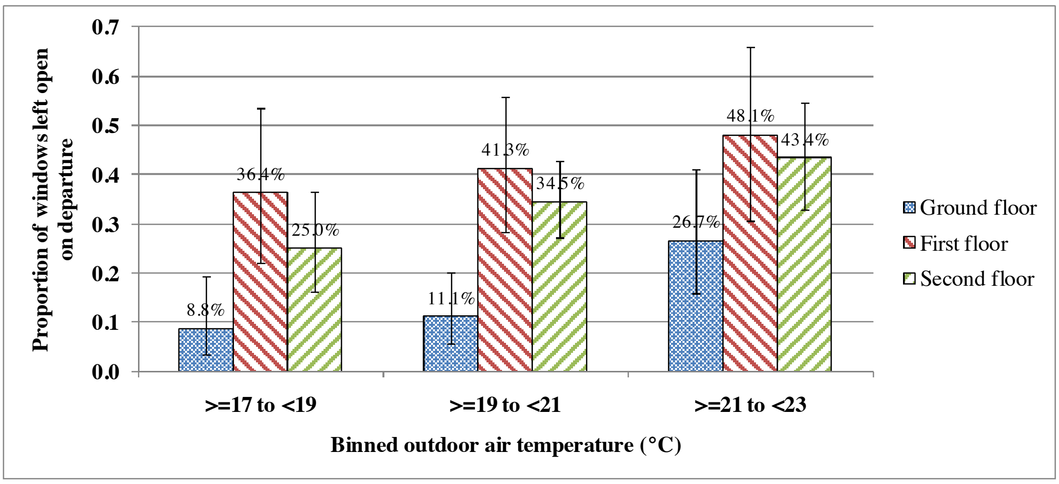

Figure 5 Proportion of windows left open as a function of outdoor air temperature for male occupied offices on different floors (10 ground floor, 6 first floor and 12 second floor offices)

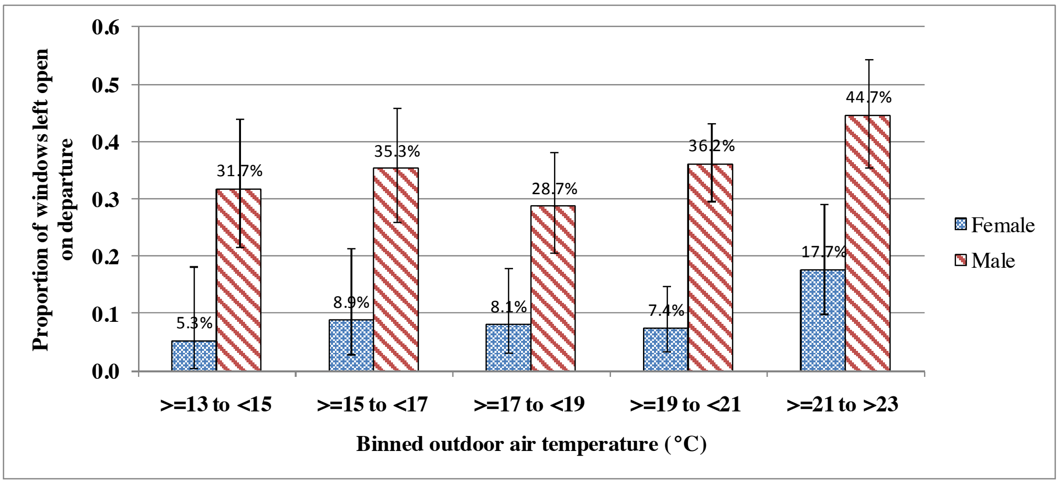

Figure 6 Proportion of windows left open as a function of outdoor air temperature for different gender of occupants (8 females and 18 males)

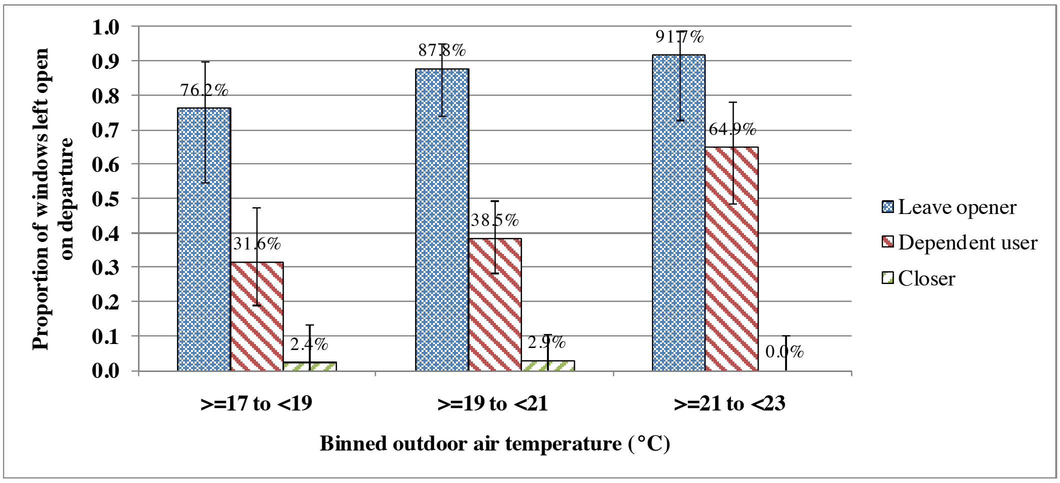

Figure 7 Proportion of windows left open as a function of outdoor air temperature for different types of window users (4 Leave openers, 7 Dependent users and 7 Closers)

Personal preference on window position during the night

During the observations, it was found that there were apparent differences in window positions overnight between occupants: some windows were rigorously closed at the end of almost every day, while some others would be left open within a very large range of temperature conditions. Differences such as these have been observed by researchers before in the operation of windows at arrival and intermediate periods of the working day (Rijal et al., 2007, Haldi and Robinson, 2009b, Yun et al., 2009), and window users have been termed 'active' and 'passive'.

Different descriptors are introduced here that better reflect the findings of this study: 'Closers' refer to people who always/habitually close the window at the end of the day, and this was observed to be largely independent of temperature; 'Leave openers' appear to leave their windows open extremely often for a large proportion of the observed period and while there is some evidence of temperature dependency. What is not clear yet is whether this is due to forgetfulness or intent, and ongoing work will explore this further. There is a group of individuals that lie in between these two extreme groups, and we have called them 'Dependent users' because their 'end of day' window use seems to respond more closely to the outdoor air temperature.

These users were grouped in a qualitative sense and three definitions were drawn from these groupings:

- 'Closers' [of window on departure] were defined as those people who, when the outdoor air temperature at the departure time was below 24°C, closed their windows on more than 80% of those days;
- 'Leave openers' were those who left windows open on more than 80% of the working days when the outdoor air temperature at the departure time was above 20°C; and
- 'Dependent users' were those who fell between the above two extremes.

Figure 7 shows the difference between these user types using these three classifications of behaviour, based only on the male subjects on the first and second floors of the building. The plot suggests that the 'Leave opener' group have a much higher probability of keeping the windows open during the night than the 'Medium users' (bigger than 30% from the observed probability). Conversely, 'Closers' almost always keep their windows shut. In the logistic regression analysis, the significant effect from the predictor type of users could also been identified – *p* values between all three types of users in the logistic regression are zero. This conclusion is also supported after the 95% level confidence intervals are considered. Although the above criterion of user type categorization is somewhat arbitrary, it does suggest that people do interact with their windows very differently at the end of working days.

Relationships between factors

Gender, floor level and personal preference all influence the operation of windows. Gender and floor level use the classification of groups within the whole building population. Personal preference, however, uses the observed characteristics of the individual to make the classification. People falling into specific gender groups, or who are members of a particular floor, can also be categorised into 'Leave opener' (LO), 'Dependent user' (DU) or 'Closer' (C). The distribution of type of user behaviour is proved to be dependent on both floor level and gender. Table 1 shows the distribution of different types of users for male occupants working on different floors, where a higher proportion of 'Closers' could be found on the ground floor, which is likely to reflect issues over security.

Table 1
User types by floor level for male subjects (10 ground floor, 6 first floor and 12 second floor)

FLOOR	C	DU	LO
Ground floor	80% (8/10)	20% (2/10)	0% (0/10)
First floor	50% (3/6)	17% (1/6)	33% (2/6)
Second floor	33% (4/12)	50% (6/12)	17% (2/12)

Table 2 shows the distribution of different types of users for female and male occupants working on the first and second floors, respectively, and suggests that females tend to be largely 'Closers', at least within the limitations of this study.

Table 2
User types by gender for occupants on the 1st and 2nd floors (8 female and 18 male occupants)

GENDER	C	DU	LO
Female	75% (6/8)	25% (2/8)	0% (0/8)
Male	39% (7/18)	39% (7/18)	22% (4/18)

These findings might suggest that when considering the performance of a building at the design stage, taking account of the types of window user could be important, especially if the intended occupants have significant bias to one category or another. Gender may be an influencing factor, but also working practice and environment and company policy may influence the prevalence of a particular user type.

DISCUSSION

Current behavioural models on 'end of day' window positions are based on environmental parameters such as outdoor air temperature (Herkel et al., 2008, Haldi and Robinson, 2009a) or indoor air temperature (Yun and Steemers, 2010), and one non-environmental factor – floor level (Haldi and Robinson, 2009a). Our survey is based on outdoor air temperature as well as some additional non-environmental parameters (occupant presence the following day, floor level, gender and personal preference on window position during the night) on the 'end of day' window position in an office building. In our analysis, the outdoor air temperature on departure was used as the only environmental parameter affecting occupants' operation of windows. A further data analysis based on indoor air temperature on departure has been carried out and the influence of each non-environmental parameter has also been identified. Further work needs to be conducted to determine which one of the environmental parameters is the better predictor for the 'end of day' window position – outdoor air temperature on departure or indoor air temperature on departure or maybe a combination of both – for inclusion with the non-environmental parameters above.

Our model is simpler than existing models in that it does not require the input of a current window state (final window state from the intermediate period) to predict 'end of day' window positions. On the other hand, existing models invoke simulation to predict the current window state, which in turn introduces uncertainties. The extent to which these factors influence accuracy of final window state predictions remains to be investigated.

CONCLUSION

The results from the comparison of window operations from one environmental (outdoor air temperature) and four non-environmental parameters (occupant presence the following day, floor level, gender and personal preference on window position during the night) have been investigated. The data gathered in the building studies here reflects the general trends observed by others in terms of the relationship with window opening and outdoor air temperature. However, non-environmental factors such as floor level, gender and an occupant's personal preference on window use are shown here to have significant influences on the 'end of day position of windows in real buildings.

Although future work is required in other buildings to strengthen the findings of this study, the authors suggest that these factors may well be important in the design of buildings and in the prediction of building performance, and also could well play a role in the way occupant education on building use is implemented to improve building performance, such as the Soft Landings initiative (BSRIA, 2011).

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